REVIEW

ADVANCEMENTS IN CHOCOLATE 3D PRINTING TECHNOLOGY: A RAPID SCOPING REVIEW AND GLOBAL LANDSCAPE ANALYSIS

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ABSTRACT – *Three-dimensional (3D) printing is a promising avenue in chocolate manufacturing, leveraging on the extrudable and solidification properties of chocolate to create highly customisable and intricate designs. The purpose of this scoping review is to uncover advancements in chocolate 3D printing technology over the last five years and identify important outcomes that can be utilised by stakeholders or knowledge users. Employing the Joanna Briggs Institute (JBI) scoping review guidelines and PRISMA-ScR as search strategies, three databases (Scopus, ScienceDirect, and IEEE Xplore) were systematically searched using keywords related to chocolate and 3D printing. Of 380 publications screened by two reviewers, 28 fulfilled the eligibility criteria (published between 2019-2023, open and full-text access, English language, and focused on chocolate 3D printing dimensions). The majority of publications were journal articles (82.1%), originating from 16 countries across Asia (35.7%), Europe (25%), North America (21.4%) and Australia (17.9%). The predominant research trend is chocolate 3D printer design, fabrication, modification, and automation (25%). Other areas of focus include consumer perception (21.4%), 3D printed chocolate product development (17%), design feature fabrication and modification (14%), ingredient incorporation in formulation (10%), studies on material properties (10%), and ink fabrication (4%). While acknowledging time and resource constraints, the evidence synthesized in this review confirms the extensive geographical coverage and research trends in the field of chocolate 3D printing research.*

Keywords: Chocolate, 3D printing, scoping review, advancements, research trends

INTRODUCTION

Cacao (*Theobroma cacao* L.) is an important global food commodity cultivated in the tropical region around the equator. While the cacao fruit is primarily harvested for its seeds or beans, it also generates valuable by-products such as pod husks and pulp (Indiarto *et al*., 2021). Cocoa beans undergo fermentation, drying, and subsequent processing to produce cocoa derivatives, including cocoa liquor, cocoa butter, and cocoa powder (Balcázar-Zumaeta *et al*., 2022). These derivatives, combined with other products like sugar and milk powder, constitute the ingredients of one of the world's most popular treats: chocolate. Chocolate is extensively used in various food items and is largely consumed for its mood-enhancing properties and nutritional benefits (Shavez *et al*., 2017; Shin *et al*., 2022; Velarde *et al*., 2018). Chocolate contains essential nutrients such as fats, carbohydrates, and proteins (Jaćimović *et al*., 2022). Chocolate with a high cocoa solid content is notably rich in biologically active compounds such as polyphenols, which possess antioxidant properties. These antioxidants play a significant role in promoting human health and preventing cardiovascular disease and cancer, among others. (Darwish *et al*., 2023; da Silva Medeiros *et al*., 2015).

With advancements in chocolate processing, particularly through the integration of additive manufacturing or three-dimensional (3D) printing technology, there is an opportunity to enhance the delivery of these health benefits. 3D printing involves the layer-by-layer fabrication of complex objects, and chocolate, with its excellent extrudability, room-temperature solidification, and universally accepted sensory properties, is well-suited for extrusion-based 3D printing (Hosseini *et al*., 2022; Karyappa & Hashimoto, 2019). This technology allows for the creation of visually appealing chocolate products with an improved nutritional profile by selectively incorporating ingredients with high nutritional value or fortifying constituents. Additionally, 3D printing can precisely adjust textures, flavours and designs, offering a possible solution to produce chocolate products that not only feature innovative shapes but also meets individual nutritional needs.

Over the last few decades, there has been a considerable volume of research published on chocolate 3D printing technology. Systematic reviews have extensively covered processing techniques, material characteristics, applications, and potential benefits of general 3D food printing. (Derossi *et al*., 2021; Li *et al*., 2019; Piyush *et al.*, 2020; W. Zhu *et al*., 2023). In 2023, VA *et al*. published a review focusing on the development of chocolate 3D printing from 1998 to 2023. The present study, in contrast, undertakes a scoping method to synthesise a report of current research on chocolate 3D printing. The objective is to assess the range, extent, and nature of chocolate 3D printing research by conducting frequency analysis, trend analysis, and thematic analysis of available literature from the last 5 years. These findings will inform effective and relevant engagement approaches for policymakers, manufacturers, and service users. Several research questions have been formulated to guide this scoping review:

RQ1:What is the range, extent, and nature of research activities done on chocolate 3D printing for the last 5 years?

RQ2:What are the important findings of this research and how do they relate thematically?

MATERIALS AND METHODS

Protocol and Registration

The scoping review protocol followed the methods outlined by the 2024 edition of the Joanna Briggs Institute (JBI) Manual for Evidence Synthesis and the checklist provided in the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) extension for scoping reviews. This protocol has not been registered on any database.

Eligibility Criteria

The eligibility criteria were defined using the Population, Concept, and Context framework. No restrictions were imposed for any of the criteria. However, as the research question does not focus on a specific condition or cohort, the population criterion was subsequently excluded from the thematic analysis. Study designs must include or relate to the specified keywords which are “chocolate" and “3D printing” or its variations: “3D printer” and “three-dimensional printing”. To narrow down the evidence scope and identify relevant studies, only published primary research studies that use chocolate 3D printing as a primary or secondary outcome variable were included. All types of study designs (qualitative, quantitative, and mixed-method studies) were accepted. To increase the feasibility and timeliness of review completion, publication date was limited from 2019 to 2023 to highlight only the most recent advancements. Additionally, only English-written, open-access, and full-text literature were accepted, while non-English texts, restricted access texts, or irretrievable items were excluded due to time and resource constraints.

Information Sources and Search Strategy

The online databases ScienceDirect, Scopus, and IEEE Xplore were searched for relevant published documents between January 1, 2019 and December 31, 2023. Searches were conducted in a single day to avoid bias from any database update. ScienceDirect and Scopus were chosen as they cover multidisciplinary subject areas and operate as keyword or bibliographic databases. Meanwhile, IEEE Xplore was chosen as it specifically covers technical literature in engineering and technology. The search terms were a combination of keywords with direct relevance to the specific research focus; “chocolate” as the material under investigation, and “3D printing”, “3D printer” and “three-dimensional printing” which refers to the manufacturing technology being studied. These keywords were chosen to maintain precision of the search strategy, avoiding broader terms that could dilute the specificity and result in less relevant findings. The search strategy was as follows: SEARCH TERM= (chocolate 3D printing OR chocolate 3D printer OR chocolate three-dimensional printing) AND LANGUAGE= (English) AND YEAR= (2019-2023). All literature searches were executed independently by a principal reviewer and a second reviewer.

Selection of Sources of Evidence

Study retrievals and screening were performed by both reviewers. Following a database search, all identified citations were collated and uploaded into Mendeley Reference Manager (version 2.111/2024). Duplicate citations from multiple databases were subsequently removed. Titles and abstracts were screened against the eligibility criteria. Articles containing the search terms in their title and/or abstract were included at this stage. Potentially relevant sources were retrieved in full when it was unclear whether the article should be included during the screening stage and a decision was made after reading the complete article. The full text of selected citations was read and assessed in detail against the eligibility criteria. Additionally, the reference lists of full-text documents and review articles were examined for additional related resources and screened using the same process. Reasons for excluding evidence sources that did not meet the inclusion criteria were recorded. Discrepancies between the reviewers at every phase during the selection process were resolved through discussion.

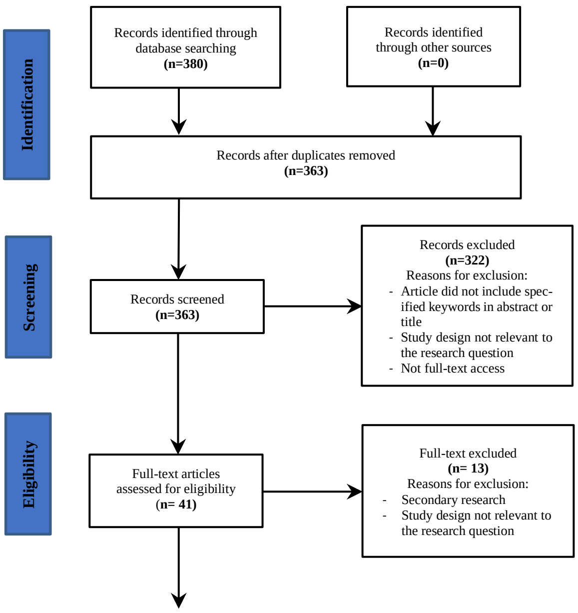
Data Extraction

Initial data extraction was performed by the principal reviewer using a data extraction tool in the form of a 49tandardized Excel form developed *a priori*. After one pilot test, data was abstracted by both reviewers independently and verified by the other. The extracted information included article characteristics (type of publication, year of publication, geographic source of publication, and journal discipline), contextual factor (country income group), and main findings. The main findings were coded by a theme and discussed categorically.

RESULTS AND DISCUSSIONS

Study selection process

In total, 380 publications were retrieved from the three databases. 363 articles remained after the removal of duplicates. The screening process further reduced the number of included articles to 41. Excluded documents did not include specified keywords in their abstracts or titles, did not have a study design relevant to the research questions, or were unavailable in full texts. The following categories were excluded: meeting abstracts, editorial material, book chapters, letters, and news items. Full-text assessment determined that only 28 studies were relevant to the research questions and met the inclusion criteria. Among the 13 excluded studies, 12 were secondary research (review articles) and the remaining article was found to be irrelevant to the research question after the complete document was read. Only duplicate documents were identified through scanning reference lists and thus retrieval of said documents was not pursued. The entire process is presented in Figure 1.



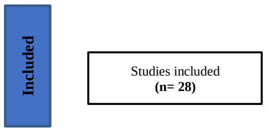


Figure 1: PRISMA flow diagram of the study selection process

Characteristics of included studies

Table 1 shows that the majority of the published articles on chocolate 3D printing were original research articles (n=23), with the remaining being conference proceedings papers (n=5). While proceedings papers are generally considered less valuable and impactful than journal articles due to their more concise reporting and less stringent review process, this review takes into account the importance of diverse information sources (González-albo & Bordons, 2011). Proceedings papers can provide insights into current research trends and cutting-edge developments, potentially driving policy changes. Nevertheless, caution is necessary when using such data for decision-making, as these papers should be accompanied by comprehensive reports of key study characteristics to ensure replicability (Kho & Brouwers, 2009).

Recent publications draw contributions from various research disciplines, particularly in science and engineering, as detailed in table 1. The Journal of Food Science stands out as the most common publishing journal discipline (53.6%). This data suggests that the chocolate 3D printing research field benefits from integrating study designs, concepts, and tools across specialised knowledge areas. For example, achieving advancements in both chocolate ink material optimization and chocolate 3D printer design requires interdisciplinary collaboration from a number of science and engineering fields. While such research offers visibility and impact through higher citations, it also poses challenges related to coordination and time investment which leads to lowered productivity (Leahey, 2018; Van Noorden, 2015).

Table 1: Publication type and journal discipline of included studies

Document characteristics		**Count (%)**
Publication type	Original research	23 (82.1%)
	Conference proceedings	5 (17.9%)
Journal discipline	Food Science	15 (53.6%)
	Materials Science	2 (7.1%)
	Pharmaceutics	2 (7.1%)
	Robotics	1 (3.6%)
	Natural Sciences	1 (3.6%)
	Systems Engineering	1 (3.6%)

Design Engineering	1 (3.6%)
Life Sciences	1 (3.6%)
Human-computer Interaction	1 (3.6%)
Multidisciplinary	1 (3.6%)
Physics	1 (3.6%)
Psychology	1 (3.6%)

Publication output and growth trend charts provide a chronological mapping of research trends and highlight the scientific interest in chocolate 3D printing. Figure 2 depicts the number of articles published from 2019 to 2023 by geographic region. Overall, there was a nearly consistent total output from 2019 to 2022 with an average of 4.75 papers per year across the three databases. Notably, there was a significant increase in 2023, with the total number of articles rising from 5 in 2022 to 9 in 2023. Overall, publication output in Asia and North America continued to grow while Europe showed fluctuating numbers. Conversely, Australia saw a complete decline after 2020, with no publications in the last three years.

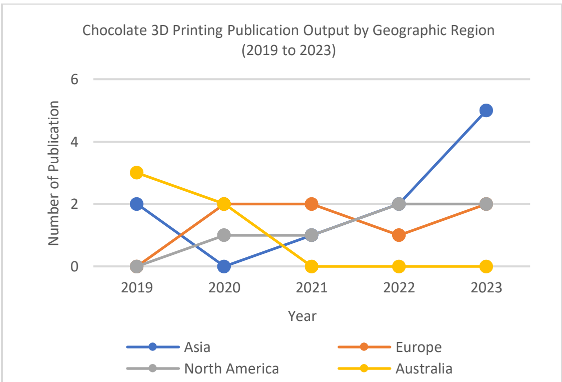


Figure 2: Annual publication output on chocolate 3D printing research by geographic region from 2019 to 2023

The choropleth map in figure 3 shows that asia is a prominent contributor to research in chocolate 3D printing within this period, accounting for 36% of total publications. The countries that contribute to this figure include Iran (1), Sri Lanka (1), Singapore (1), Indonesia (1), China (1), Taiwan (1), Turkey (1), South Korea (1), and Japan (2). Europe follows with 25%, contributed by Greece (2), the Netherlands (3), Switzerland (1), and the United Kingdom (1). North America accounts for 21% with contributions from the United States of America (4) and Canada (2). Australia represents 18% with 5 publications.

More than half of the research conducted in the last 5 years was carried out in high-income countries (9, 56.3%) followed by upper middle-income (5, 31.3%) and lower middle-income countries (2, 12.5%) as highlighted in figure 3. The difference in publication output highlights how income diversification influences the choice of technology. This can be attributed to factors such as resource availability or input; high-income countries generally have advanced research institutions with better access to key resources such as information, land, labour, and capital required to use the technology successfully, owing to the substantial financial investments from the business sector (Gonzalez-brambila *et al*., 2016). According to Acharya & Pathak (2019), only about 10 countries account for 80% of the global spending on research and development (R&D) as of 2019. North America (Canada and United States) and Western Europe (the Netherlands, Switzerland, and United Kingdom) were the lead with 46.1% research followed by East Asia (China, Japan, Taiwan, Korea) and the Pacific (Australia) with 40.6%. The lack of research in low-income countries may reflect different research or government priorities, as R&D investments in these countries constitute less than 1% of their GDP (Vergara, 2023). As for Malaysia, further assessment is required to evaluate the country's potential as a contributor in this particular field by analysing its research output, collaborations, and institutional strengths.

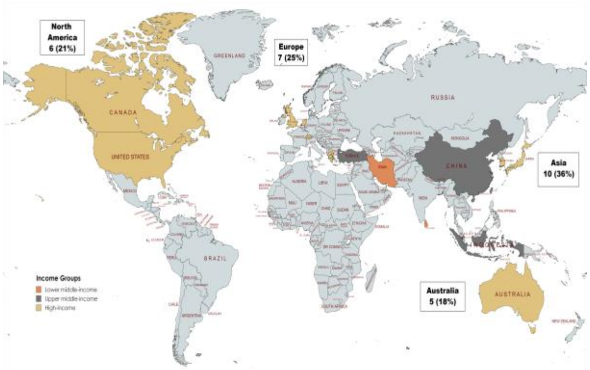


Figure 3: Choropleth map of chocolate 3D printing research publication distribution by geographic region and income group

Thematic analysis of included studies

The primary findings from the studies on chocolate 3D printing that were included in the selection process are summarised in Table 2. These findings were systematically extracted and organized into thematic groups to enable the identification of key trends or prevailing areas of focus within this particular field. This thematic approach also provides insight into potential areas for further exploration and innovation in this emerging technology.

3D printer design, fabrication, modification, and automation
Design is defined as the preliminary sketch or outline of the main features of 3D printers, while fabrication refers to the construction of the printer from diverse and often standardised parts. Modifications encompass the act, process, or result of altering the hardware, software, or both, of existing 3D printers. Automation refers to the process of putting the 3D printing operation or system under the control of mechanical or electronic devices (Merriam-Webster, n.d).

Suzuki *et al*. (2019) fabricated an electrostatic inkjet micro 3D chocolate printer featuring acrylonitrile butadiene styrene (ABS) microfibers within the nozzle to facilitate Taylor cone formation, allowing high-precision and stable continuous chocolate printing. Sylvester *et al*. (2020) modified the Porimy 3D chocolate printer by creating a custom printer bed with an integrated water recirculation system and fan for immediate chocolate solidification. The 3D chocolate samples created using the modified printer revealed that cross-support is more effective than parallel-support in stabilising hexagonal-shaped constructs. Meanwhile, Raiapaksha *et al*. (2021) utilised a pressure-pump mechanism to provide additional pressure on melted chocolate for continuous printing, which addresses the limitation of syringe-type extruders. Lanaro *et al*. (2020) and Ntagios *et al*. (2023) developed cost-effective 3D printers– a custom reservoir-based system called the Additive Manufacturing Melt Extrusion (ADDME) 3D printer and a multi-material 3D printer utilising a direct ink writing double extrusion mechanism with active material mixing at different ratios. The printing performance of both printers was evaluated through line-testing with chocolate. Hosseini *et al*. (2022) discussed various aspects of an extrusion-based chocolate 3D printer, including 3D table design, electronics, printer performance, and addition of hydrocolloids. Ma *et al*. (2023) adapted an extrusion-based 3D printer with a pneumatic system and computer vision software that measures instant extrusion rate and filament width under constant extrusion pressure. This allowed for motion flexibility of white chocolate spread samples without affecting extrusion flow, thus improving its printing performance.

Consumer perception
Scheele *et al.* (2022) measured consumer response regarding the shape, taste, and fidelity of 3D printed designs with varying shape complexity and ingredients. Their findings concluded that consumers preferred more complex shapes and designs with high fidelity to their Computer-Assisted Design (CAD) counterparts. Additionally, chocolate was favoured over marzipan as an ink material. Two studies investigated the impact of labelling and information on consumer perception of 3D printed products. Pratama & Herianto (2023) highlighted the importance of detailed information for consumers specifically in Indonesia, which includes aspects such as shape, texture, size, aroma, construction resistance, and product colour. Feng *et al*. (2022) concluded that while labelling chocolate as “3D printed" increased the perception of product quality, providing visual information about the printing process and product-specific benefits did not significantly increase perceived quality or sensory acceptance. In contrast, a survey by Mantihal *et al*. (2019) demonstrated that consumer acceptance of 3D products and opinion on the benefits of 3D printing technology significantly improved after a visual demonstration of the printing process using chocolate samples. Furthermore, consumers expressed a preference for 3D-printed chocolate with 25% infills compared to 50% and 100% in terms of hardness. Ogata *et al*. (2023) investigated the influence of chocolate shapes on taste perception and concluded that Bouba-shaped (rounded) chocolate pieces were perceived as sweeter than Kiki-shaped (angular) ones.

3D chocolate product development
Khemacheevakul *et al*. (2021) introduced a prototype of sugar-reduced 3D printed chocolate by layering high and low-sugar chocolate without influencing overall liking. Kim *et al*. (2022) formulated a cold-extruded chocolate ganache with a 30% whipped cream ratio for optimal shape retention. Their research revealed that cocoa powder at a 20% concentration prevents fat separation of the emulsion and contributes to the load-bearing capacity of the printed chocolate, thus overcoming destabilisation issues due to temperature changes. Paediatric-friendly 3D printed chocolate-based oral dosage forms developed by Chachlioutaki *et al*. (2022) and Karavasili *et al*. (2020) allowed for accurate prescription of dosages to prevent overdose and met all required quality standards. Cheng *et al*. (2023) created edible electronics prototypes using 3D printed chocolate embedded with an edible gold leaf as the electrode material. This product can encode information and be destroyed functionally through ingestion.

Design feature fabrication and modification
Mantihal *et al*., (2019) created three internal structures of 3D printed chocolate using the star, Hilbert curve, and honeycomb infill patterns and determined that the star and honeycomb patterns at 60% infill produced the most stable structures. *Zhu et a*l. (2020) varied the thickness of chocolate layers and deduced that sweetness perception can be altered through bite-to-

bite variation, although this was less preferred compared to a homogeneously coated product. Scheele *et al*. (2020) assessed the printability of different design features and concluded that the overhang angle for chocolate cannot be less than 35°. Additionally, it is more difficult to create well-formed holes using chocolate compared to using marzipan. Burkard *et al*. (2023) 3D printed multiphasic chocolate and cream cheese in different configurations resulted in different temporal dominance profiles, all of which showed chocolate dominance towards the end of consumption.

Incorporation of ingredients in chocolate formulation

Mantihal *et al*. (2019) utilised magnesium stearate powder and plant sterol powder to facilitate processing during auger-type extrusion-based printing of dark chocolate. They concluded that both additives increased yield stress values without affecting melting behaviour of the chocolate. Additionally, they enhanced coefficient of friction, thus reducing slippage during auger extrusion. Erunsal *et al*. (2023) found that the addition of carob extract as a natural sweetener produced highly moist, viscous, and soft 3D printed chocolates. Replacing 30% of the dark chocolate composition with carob yielded a stable construct with a smooth surface and high printing accuracy during extrusion-based printing. You *et al*. (2023) explored fat reduction in 3D printed chocolate by replacing cocoa butter with water-in-cocoa butter emulsions. The resulting product was able to maintain its polymorphic form V and shear-thinning fluid behaviour. Meanwhile, Huang *et al*. (2023) addressed solidification issues in white chocolate extrusion by incorporating oleogels such as monoglycerides (MAG), sucrose fatty acid ester (SE), and hydroxypropyl methylcellulose (HPMC). Effective extrusion and solidification were achieved with MAG and SE concentrations exceeding 2%.

Studies of chocolate material properties

Rando & Ramaioli (2021) investigated how process conditions, as well as the rheological and heat transfer properties of dark chocolate, affect print stability during paste extrusion. They successfully printed 3D structures at 18°C within a printing velocity range of 4 to 12 mm/s.

3D ink fabrication

Karyappa & Hashimoto (2019) fabricated chocolate-based inks that do not require hot-melting temperature control by mixing chocolate syrup, hazelnut chocolate spread, and cocoa powder. The resulting ink exhibited solid-like characteristics with zero shear yield stress, was shear thinning, and could create self-supporting layers at room temperature.

Table 2: Thematic categories of main findings from chocolate 3D printing research studies

Theme categories	**Count (%)**
3D printer design, fabrication, modification, and automation	7 (25%)
Consumer perception	6 (21.4%)
3D chocolate product development	5 (17.9%)
Design feature fabrication and modification	4 (14.3%)
Incorporation of ingredients in chocolate formulation	4 (14.3%)
Studies of chocolate material properties	1 (3.6%)
3D ink fabrication	1 (3.6%)

CONCLUSIONS

Over the last five years, advancements in chocolate 3D printing research have recorded a broad geographic coverage in middle- and high-income regions. The number of research articles published annually showed minor fluctuations, but there was a notable surge in 2023. Thematic clusters of research topics include 3D printer development, consumer acceptance, product innovation, design features, material properties, ingredient incorporation, and ink fabrication. These findings were disseminated across various journal disciplines, suggesting opportunities for collaboration. It is crucial to acknowledge the limitations of this rapid scoping review. Due to time constraints, the review relied on a limited number of databases, included only English-language literature, and excluded publications with restricted access. Hence, valuable evidence from other sources may consequently be overlooked, making the review incomprehensive. Additionally, the methodological quality of the included studies was not assessed which may affect scientific rigour. Despite these limitations, this review is intended to provide valuable insights into identifying collaboration networks, uncovering research hotspots, and forecasting future directions in chocolate 3D printing. Promising areas for further research include optimizing printing conditions for complex geometries by adjusting rheological and thermal properties of chocolate, refining process conditions, as well as gaining a deeper understanding of sintering dynamics. Additionally, further investigation is needed to explore the impact of natural sugar alternatives on chocolate printability, addressing the growing interest in low- or no-sugar chocolates. The development of room-temperature chocolate-based ink which overcomes the limitations of hot-melt extrusion methods also presents new practical applications for chocolate 3D printing and other temperature-sensitive food items.

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